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EVALUATION OF SELECTED COMPUTER MODELS FOR MODELING PYROTECHNIC AND PROPELLANT DEVICES

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Final Report

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A variety of analytic computer models are available and have been used successfully to predict performance in pyrotechnic systems, providing an inexpensive and quick method for initial validation of the performance of a system design. The authors have assessed several of those available at Naval Ordnance Station, Indian Head, MD, including several of the standard thermodynamic codes (NASA-Lewis, PEP, BLAKE, TIGER) as well as lumped parameter ballistic codes (CADPROG, EBED, ROCIGN), delay burn

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20. ABSTRACT (Continued)

rate codes (HARDT), and ignition requirements analysis (Bryan-Lawrence). The use, characteristics, and outputs of the various codes are discussed with emphasis on limitations and cautions required when applying these techniques to predict performance of pyrotechnic systems.

FOREWORD

This work was performed at the Naval Ordnance Station, Indian Head, MD, from January 1988 to December 1988.

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Head, Manufacturing Technology Department

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INTRODUCTION

The design and development of new pyrotechnic systems has an inherent performance requirement: the system must be capable of producing a specified effect for a given time, and it must perform within certain time (and often spatial) constraints. The system must also meet these performance requirements with an acceptable level of reliability.

Ensuring that these design objectives are met is frequently difficult, time consuming, and costly, given that performance criteria and operational conditions may often be new and untried. The effects of changes to standard pyrotechnic formulations may be reasonably estimated within a given range by a competent designer, but often other changes are less likely to produce predictable effects. For example, performance changes induced by altering the particle size distribution or particle shape of either fuel or oxidant are poorly understood. Changes to the molecular weight of a polymeric component may affect not only performance but also the manufacturing process. Also, with the increasing cost and time involved in development of pyrotechnic devices, it is usually not possible for the designer to experimentally evaluate many of the reasonable design options available. Often some degree of "intuition" is injected into the process. This may lead to elimination of the ideal, but nonobvious, solution to the problem at hand.

As an aid to the designer, the application of computer modeling is becoming increasingly popular in the initial phases of development efforts. Computer models are relatively new and untried in the field of pyrotechnics; their more popular uses are for high explosives and propellant systems. However, there is increasing interest and use of explosive and propellant models for pyrotechnics and their adaptation has had varying degrees of success.

COMPUTER MODELING

The use of computer models allows the designer to develop a prediction capability for a range of conditions and determine the influence of individual parameters. Models can also aid in the understanding of observed phenomena and reduce the cost, complexity, and scale of feasibility or verification tests.

At the Naval Ordnance Station (NAVORDSTA), Indian Head, MD, there are three basic areas relating to pyrotechnics where computer modeling may be employed for one or more of the reasons mentioned previously.

(1) Computing the thermodynamic state of any heterogeneous reacting system and derivation of a range of thermochemical parameters of importance, such as flame temperature, heat capacity, enthalpy, products of combustion

(2) Predicting ignition energy requirements of propellant systems and modeling the behavior of pyrotechnic igniter systems and the subsequent response of downstream materials

(3) Modeling the dynamic performance of pyrotechnics.

Each of these areas are treated in the following paragraphs.

Thermochemical Modeling

Many computer programs have been developed to characterize the thermochemical behavior of heterogeneous multiphase reacting systems (1,2,3,4,5,6,7). Most have been developed because of the need for thermochemical data, the complexity and large number of nonlinear algebraic equations that must be solved simultaneously, and the need to handle a variety of chemical problems. The more familiar of these computer codes are the NASA-Lewis code CEC76 (1,2) or CEC72 for the earlier version, BLAKE (6) and TIGER (7). All these codes attempt to model the combustion process considering only the initial and final states of the reacting system using either a free energy minimization technique or an equilibrium constant approach.

At NAVORDSTA, CEC76 (or variations of it), BLAKE, and the Propellant Evaluation Program (PEP) (5) are available. CEC76 is the most frequently used of the three codes because of its emphasis on propellant systems and its larger database.

Using the CEC76 code and assuming a given reacting mixture of components (fuels + oxidants), there are many combinations of conditions for which computations may be made. On the basis that any thermodynamic state may be specified by assigning any two state functions, the thermochemical data of the reacting system may be determined using, as inputs:

(1) Temperature and pressure
(2) Enthalpy and pressure
(3) Entrophy and pressure
(4) Density (or volume) and temperature
(5) Entrophy and volume (or density)
(6) Internal energy and volume (or density).

The range of options in the code allows for additions to the reactants, alterations to the proportions, etc. Typical input and output data for a pyrotechnic composition containing 51.3% magnesium, 28.5% Teflon, and 15.2% Viton A (MTV) reacting in a 5% argon atmosphere are given in Tabie I. Using these codes, the thermochemical behavior of reacting systems may be studied with changes in pressure, temperature, density, volume, etc. Figures 1 and 2 also show some of the typical data obtained using this code.

TABLE I. TYPICAL INPUT AND OUTPUT DATA FOR CEC76 CODE

Reactants MTV (Input)

Mg	1.000		0.000		0.000	51.299999	0.00	S	298.150	F
C	2.000	F	4.000		0.000	28.500000	−196100	S	298.150	F
C	5.000	H	3.500	F	6.500	15.200000	−332700	S	298.150	F
Ar	1.000		0.000		0.000	5.000000	0.00	G	298.150	O

Characteristic or product	Output at —			
	1 Atm	100 Atm	500 Atm	1000 Atm
Thermodynamic properties				
Pressure (MPa)	0.10133	10.133	50.662	101.32
Temperature (K)	2195.7	2742.8	3155.0	3407.6
RHO, g/cc	2.9059-4	2.7617-2	1.9305-1	6.3517-1
H, cal/g	−829.12	−829.12	−829.12	−829.12
U, cal/g	−912.46	−916.81	−891.85	−867.25
G, cal/g	−4041.22	−4397.31	−4787.26	−5068.55
S, cal/(g)(K)	1.4629	1.3009	1.2545	1.2441
Mol wt (M)	52.356	62.156	99.957	177.602
(DLV/DLP)T	−1.19674	−1.08262	−3.40431	−1.98651
(DLV/DLP)P	4.2595	1.8048	11.2392	4.9139
CP, cal/(g)(K)	2.3855	0.6665	1.3204	0.6475
Gamma	1.1012	1.0795	0.6656	0.6373
SON VEL, m	619.7	629.3	418.0	418.8
Mole fractions				
Ar	0.02726	0.03801	0.03847	0.03829
Acetylene	0.00011	0.00099	0.00286	0.00534
H	0.00081	0.00083	0.00099	0.00101
HF	0.00452	0.00095	0.00081	0.00087
H_2	0.03874	0.03178	0.02629	0.02664
Mg	0.34819	0.33058	0.16066	0.05593
MgF	0.06461	0.04565	0.03144	0.01597
MgF_2	0.07254	0.01288	0.00715	0.00402
MgH	0.00163	0.01887	0.02642	0.01852
Mg_2	0.00011	0.00796	0.01195	0.00457
Mg_2F_4	0.00010	0.00003	0.00002	0.00001
C(gr)	0.29039	0.29434	0.29348	0.28564
Mg(l)	0.00000	0.00000	0.16608	0.29943
MgF_2(l)	0.14098	0.21705	0.23299	0.24267

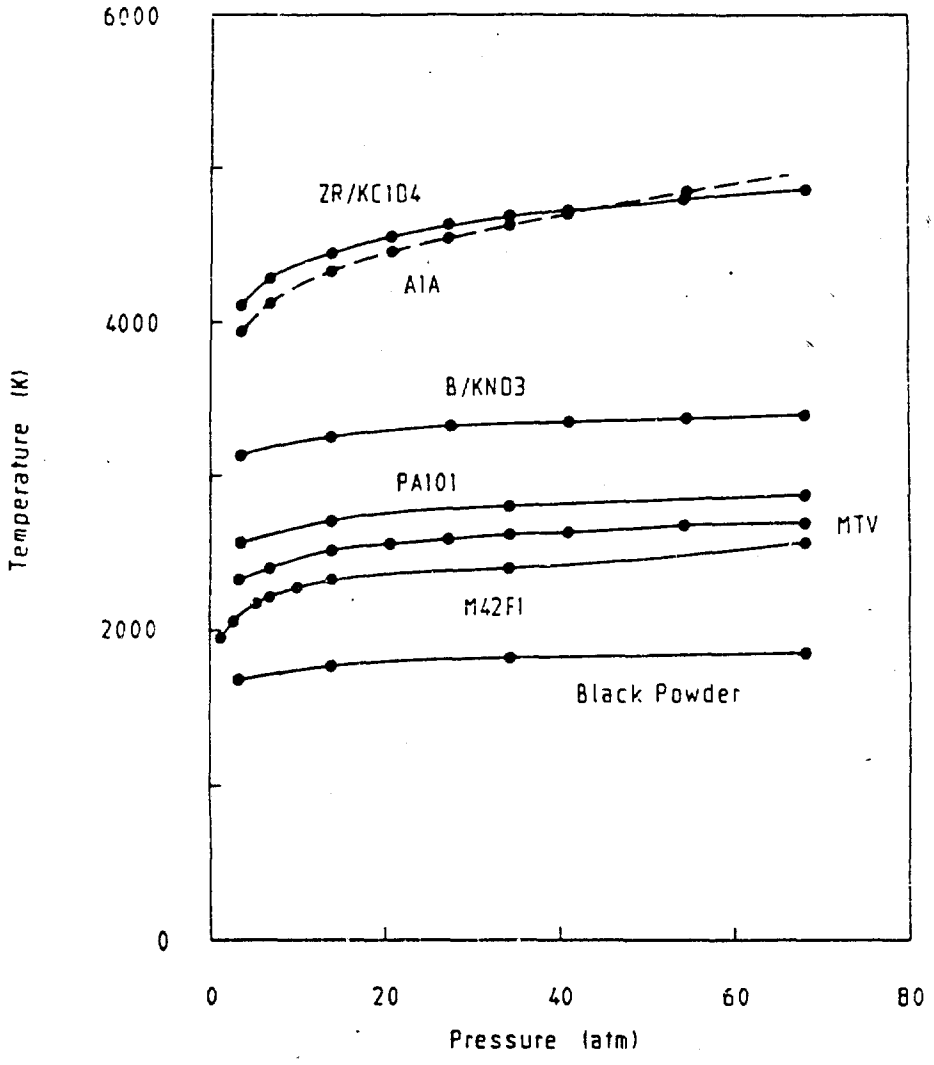

FIGURE 1. RELATIONSHIP BETWEEN PRESSURE AND TEMPERATURE FOR SOME PYROTECHNIC IGNITION COMPOSITIONS

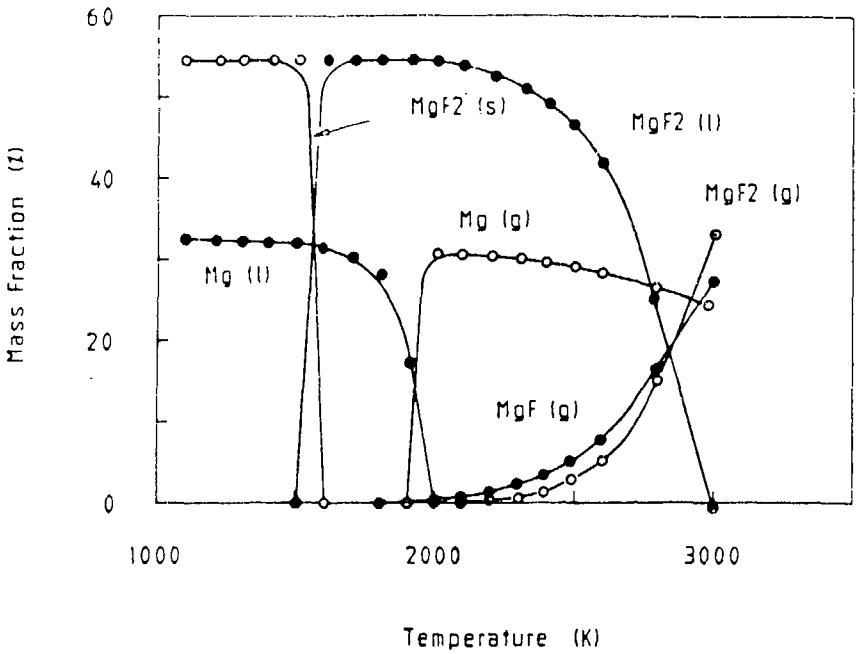

FIGURE 2. PRINCIPLE CONDENSED PHASE REACTION PRODUCTS FOR REACTION OF MTV COMPOSITION AT 25 ATMOSPHERES

Figure 1 shows the computed relationship between the pressure and temperature for some typical pyrotechnic ignition compositions, ranging from black powder through percussion primer compositions (PA101, M42F1), igniter compositions (MTV, B/KNO_3, Zr/$KC1O_4$), and a delay train output composition (A1A). A listing of pyrotechnic formulations cited throughout the text is given in the Appendix. These data can assist in the choice of the igniter composition, given a pressure requirement and a knowledge of the temperature required. For example, Figure 1 shows that Zr/$KC1O^4$ generates a significantly higher temperature than the other compositions over the entire pressure range examined. It also illustrates that large changes in pressure produce only marginal changes in the temperature.

However, as is well known in the design of pyrotechnic igniter systems, both the mode of heat transfer and the type of output products are chemically and physically important in determining the performance of a composition. Figure 2 illustrates the computed makeup of the principle condensed-reaction products from an MTV reaction at 25 atm pressure and a range of temperatures. These data aid in predicting which species are important for ignition, where heat losses are occurring (e.g., phase changes), where the energy of the igniter is being used, and the overall energy of the reacting mixture.

Most of the popular thermochemical codes are based on similar thermodynamic theory. CEC76 uses a minimization of free energy technique to satisfy the equilibrium conditions, whereas PEP uses an equilibrium constant technique. A comparison between the output produced by these two techniques for a boron/potassium nitrate/laminac resin ignition composition is shown in Table II. Clearly both codes give similar answers, the major difference being the range of output data. CEC76 uses an ideal gas equation of state in the calculation process whereas BLAKE and TIGER use a modified Virial equation of state. Again, a comparison of the output of the CEC76 and BLAKE codes (Table III) shows that the major difference is the different thermodynamic functions calculated and the extent of the database.

TABLE II. COMPARISON OF COMPUTER OUTPUT FOR B/KNO_3/RESIN USING PEP AND CEC76 CODES

Characteristic or product	PEP at —		CEC76 at —	
	68.02 Atm	1.00 Atm	68.02 Atm	1.00 Atm
Thermochemical Parameters				
Temperature (K)	2719	2081	2895	2475
Enthalpy (cal g^{-1})	−870.2	−1210.01	−862.9	−862.9
Density (g cm^{-3})	—	—	0.0186	0.0003
C_p (cal g^{-1} K^{-1})	—	—	1.4742	2.6038
Gamma	1.1121	1.1048	1.0700	1.06237
Entrophy (cal K^{-1})	1.445	1.445	—	—
Reaction Products				
B_2O_2 (g)	—	—	4.37	8.87
B_2O_3 (g)	—	—	1.39	0.86
CO (g)	12.28	12.94	13.00	13.00
HBO (g)	0.09	—	4.12	4.72
HBO_2 (g)	1.48	0.49	0.24	0.08
K (g)	25.53	26.14	1.31	6.68
KBO_2 (g)	—	—	25.45	19.66
N_2 (g)	0.31	0.04	2.79	3.10
B (1)	—	—	19.89	14.27
BN (s)	24.10	26.16	21.09	20.14
K_2 (g)	0.75	—	—	—
H_2 (g)	5.50	6.18	4.23	3.91
KCN (g)	0.97	—	0.09	0.02
B_2O_3 (1)	9.23	11.83	—	—

TABLE III. COMPARISON OF COMPUTER OUTPUT FOR MTV USING BLAKE AND CEC76 CODES

Characteristic or product	BLAKE at —		CEC76 at —	
	500 Atm	1000 Atm	500 Atm	1000 Atm
Thermochemical Parameters				
Temperature (K)	3180	3496	3155	3407
Enthalpy (cal g^{-1})	−829.1	−829.1	−829.1	−829.1
Density (g cm^{-3})	0.191	0.616	0.193	0.635
C_v (cal K^{-1})	0.568	0.499	—	—
C_p (cal g^{-1} K^{-1})	—	—	1.320	0.648
Gamma	—	—	0.666	0.637
Reaction Products (mass fraction)				
Ar (g)	0.050	0.042	0.050	0.050
C_2H_2 (g)	—	0.004	0.002	0.005
H_2 (g)	0.016	0.002	0.002	0.002
Mg (g)	0.125	0.042	0.127	0.044
MgF (g)	0.045	0.021	0.044	0.022
MgF_2 (g)	0.014	0.008	0.014	0.003
MgH (g)	0.022	0.016	0.022	0.015
Mg_2 (g)	—	—	0.019	0.007
C (gr)	0.115	0.112	0.115	0.112
Mg (l)	0.151	0.248	0.131	0.238
MgF_2 (l)	0.472	0.496	0.472	0.494
Total	0.996	0.991	0.998	0.992

Each of these codes has limitations and disadvantages. Comparing the free energy minimization technique with the equilibrium constant technique shows that both methods reduce to the same number of iterative equations when converging to a solution, but the free energy technique does it faster. The free energy technique is also easier in terms of bookkeeping and better in testing for condensed-phase products. As noted above, the CEC76 uses an ideal gas equation of state but a heterogeneous reacting mixture at a temperature of several thousand degrees Kelvin is anything but ideal.

A practical limitation to all the codes is their varied ability to handle condensed-phase reaction products which, in pyrotechnics, may be up to 80% or more of the reaction products, particularly as temperatures decrease. TIGER was developed for gun systems, and hence is adapted for high pressures (10,000 psi) and predominantly gas-phase reaction products. BLAKE is a more useful code for pyrotechnics but has significant problems converging to a solution when several different condensed-phase products are present (8,9). CEC76, although arguably more versatile for pyrotechnics, still has problems with condensed phases. It can, however, handle many different condensed phase products and successful convergence has been achieved with up to 99% condensed products (10). However, this type of result is often not achieved without a knowledge of the reaction mechanism, persistence, and time.

Other drawbacks to these codes are their limitation to equilibrium conditions (which frequently are not achieved in reality), the inability to include chemical kinetics, and the exclusion of thermal effects; i.e., heat liberated to cooler surroundings and diffusion of the atmosphere into the reacting zone. Effects of heat losses are generally small compared to the effects of failure to reach equilibrium resulting from kinetics; e.g., if there is not enough time for condensation nuclei to form before the reacting mixture is dispersed, then a predicted solid phase will

never form. Caution must also be exercised as the computed products listing is limited to only those chemicals present in the data file. Consequently, errors may be introduced through omission of ingredients — this is particularly important in pyrotechnic compositions, where organic waxes, dyes, or binders may be present in large proportions.

Given all the limitations, there are, however, many examples of the use of these codes to predict the thermochemical behavior of a range of pyrotechnic-based materials with varying degrees of success (10,11,12,13,14,15).

Ignition Modeling

The current trend toward high technology, sophisticated rocket motors that require greater accuracy in the prediction, and control of ignition transients places increasing importance on the behavior of the rocket igniter. To provide the designer with the required information, many computer codes have been developed which model the igniter performance and the propellant response (16,17,18,19). These codes are of interest to the pyrotechnist also as many of the igniter designs are based on pyrotechnic materials such as B/KNO_3, MTV, and black powder.

In the initial design of an igniter at NAVORDSTA, the propellant ignition energy requirements and consequently the mass of igniter material are evaluated using the Bryan-Lawrence equation. This equation,

$$Q = 38\,[A\,q_c\,(L_g\sqrt{4\pi A_p/A})^{0.59}]^{1.06}$$

where Q = total energy required for ignition
A = total area exposed to igniter products
q_c = experimental ignition energy per unit area of propellant
L_g = propellant grain length
A_p = port area

was developed from locked stroke compressor ignition tests of 51 in-service propellants (20). Once Q is calculated, the mass of igniter composition required is determined from

$$Q = m\,\Delta H_{comb.}$$

where m = mass of igniter material
$\Delta H_{comb.}$ = heat of combustion of igniter material

Although the original data on which the Bryan-Lawrence equation is based encompassed the propellants widely used some 30 years ago, recent analysis of NAVORDSTA rocket motors of current design shows it to be still appropriate in estimating ignition energy requirements. In recent studies, a CO_2 laser has been used to ignite propellant and pyrotechnic samples. The relationship between laser energy and ignition delay (time to first light) was determined and the value of q_c obtained by extrapolation of the data to a 3-ms ignition delay.

A key limitation is that the Bryan-Lawrence equation provides only an estimate of ignition energy requirements. It takes into account only the calorific output of the ignition material. There is neither weighting of internal surface areas (A) to account for the directional nature of igniter output, nor are factors considered such as igniter mass flow rate, energy flux, partitioning of the energy between gas and condensed phase, reliability/safety margins,

or expulsion of unreacted ignition material from the rocket motor. For these reasons, the Bryan-Lawrence equation provides only a rough estimate (often low by up to 50%) of the appropriate igniter charge weight. Actual test firings of approximately the computed charge weight value are still required to optimize igniter output.

With the advent of computers and a more detailed knowledge of the ignition transient behavior, many models were developed to model ignition processes. These models may be subdivided into three major families:

P(t) Model: This model is often called the lumped parameter model and behavior is calculated as a function of time only. No spatial evaluation is included so all the thermodynamic variables (pressure, temperature, combustion products, etc.) are constant throughout the volume at any time. This assumption is, however, invalid for rocket motors with a high loading density or a high length-to-diameter ratio. The P(t) model also assumes the internal temperature is approximated by T_f (flame temperature) and energy losses from the combustion products are often ignored or treated simplistically. The advantage of the P(t) model is the rapid computing speed and the simplicity of the analysis because of the linear equations used.

P(x) Model: The P(x) or quasi-steady state or 1-D model assumes that the flow of gas along the motor chamber is quasi-steady at any time and computations are a function of distance rather than time. Since time-dependent variables are neglected, the chamber filling time and flame-spreading times are neglected. The P(x) model is simple computationally, but is inadequate to describe motors with high volumetric loading densities and large length-to-diameter ratios.

P(x,t) Model: Also called the temporal and spatial flowfield model, the P(x,t) model includes variation in both the axial distance along the motor chamber and time-dependent variables. This model includes flame spreading and erosive burning and has been used successfully in predicting the combustion of solid propellant motors where convective heating dominates and where the functioning time is shorter than the flame-spreading time.

All these models have been used to describe the behavior of solid propellant ignition and stable combustion.

NAVORDSTA has several codes which are used to predict igniter performance and the propellant response. These include the ROCIGN Code (18) and more recently, the EBED Code (19). The general physical makeup of the models is shown in Figure 3. The igniter cavity products are produced in the gas phase (gas/vapor) or condensed phase (liquid/solid), which then vent into the propellant chamber via a series of axial holes. Flow is assumed choked, rapidly expanding into the propellant chamber and then moving downstream before exiting at the nozzle.

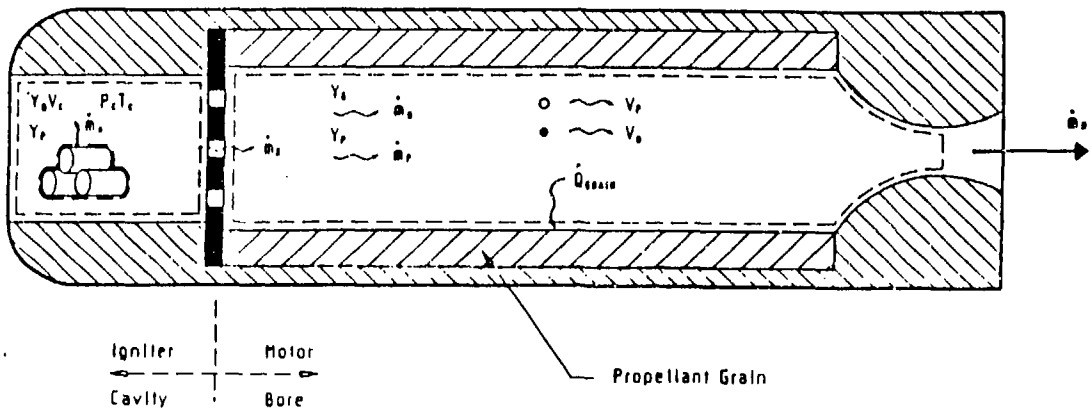

FIGURE 3. COMPUTER MODEL PHYSICAL ARRANGEMENT

The ROCIGN code uses a lumped parameter model for the igniter to predict:

(1) Maximum igniter pressure
(2) Time to P_{max}
(3) Burn time
(4) Effect of composition variables
(5) Effect of igniter design.

The code uses the P(t) model because of its simplicity but assumes that the energy losses from the combustion products are negligible — so the internal temperature is closely approximated by the flame temperature. Another difficulty with using the ROCIGN code in this manner is the relative abundance of condensed species in the igniter combustion products and the possible ejection of still combusting or uncombusted material from the igniter cavity. Once the igniter has been modeled, the code uses a P(x) model to compute the axial flowfield profile down the rocket motor bore (pressure, propellant grain temperature, gas temperature, gas velocity, etc.).

Figure 4 presents the computed and experimental pressure-time history for a rocket motor igniter containing 48 g of MTV pellets. Clearly there is good agreement between the predicted behavior and the actual igniter performance. However, as with any computer model, it may be tailored to any situation by altering the value of one or more of the assigned input parameters. Figures 5 and 6 illustrate that small changes in some of the critical inputs may cause large changes in the pressure-time relationship. Consequently, the input parameters must be known with a large degree of accuracy.

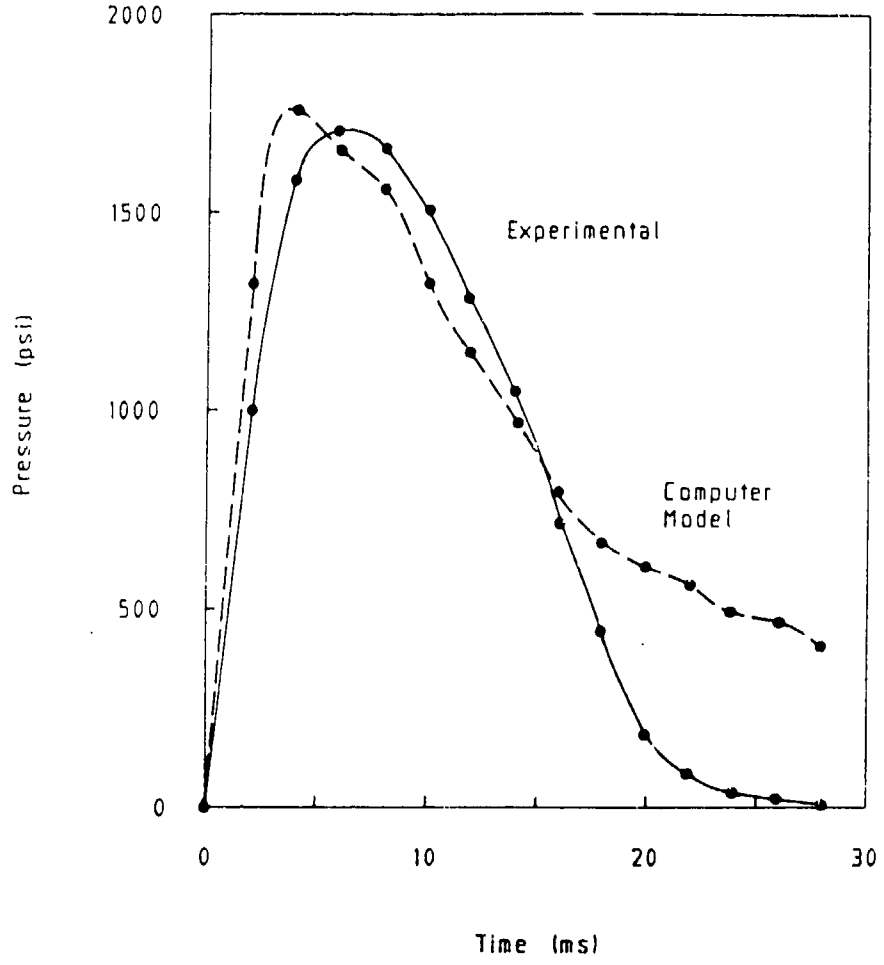

FIGURE 4. COMPARISON BETWEEN EXPERIMENTAL PERFORMANCE OF AN IGNITER AND COMPUTER CODE PREDICTION USING ROCIGN

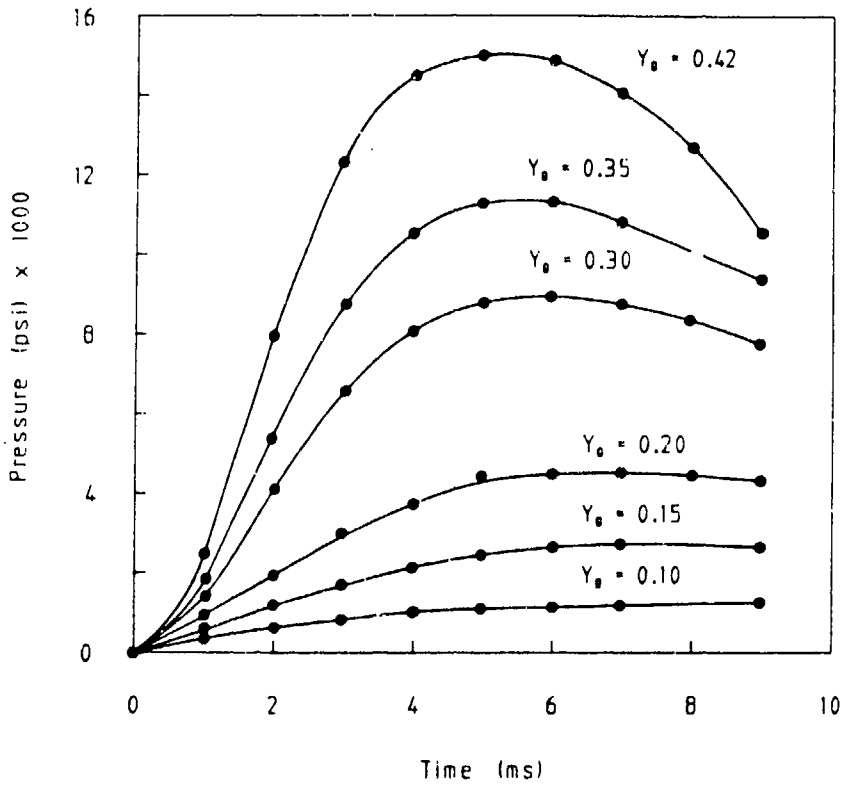

FIGURE 5. PRESSURE/TIME CURVES FOR MTV WITH DIFFERENT GAS FRACTIONS (Yg) IN THE REACTION PRODUCTS COMPUTED USING ROCIGN

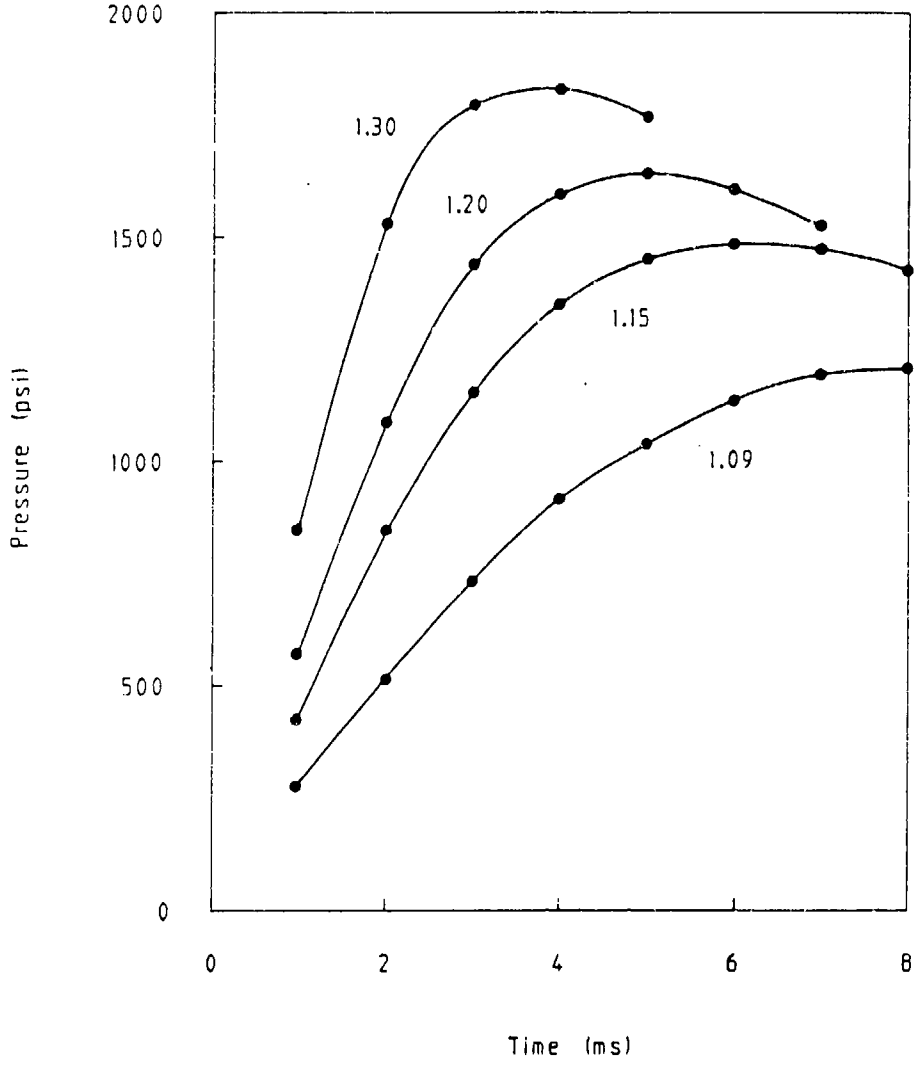

FIGURE 6. PRESSURE/TIME VALUES FOR MTV USING A RANGE OF HEAT CAPACITY RATIOS (GAMMA) FOR Yg = 0.10, COMPUTED USING ROCIGN

Many of these input variables (e.g., C_p/C_v, C_p, T, % gas products) are calculated using the thermochemical models discussed earlier. The data therefore suffer from the assumption of ideality, equilibrium conditions, instantaneous and complete ignition, and that combustion takes place entirely in the igniter cavity. Some of these assumptions are clearly incorrect. High-speed photographic examination of open-air firings of MTV pellet igniters shows a significant proportion of the combustion occurs outside the igniter cavity; i.e., in what would be the motor cavity volume. Also, the high percentage of condensed phase products gives not only two-phase flow but variability of the product composition with pressure, making the assumption of a constant ratio of gas to condensed-phase products invalid. Figures 7 and 8 show a comparison between the predicted energy flux for three typical igniter materials. However, given the large differences between the proportions of gaseous reaction products, this type of prediction may be questionable.

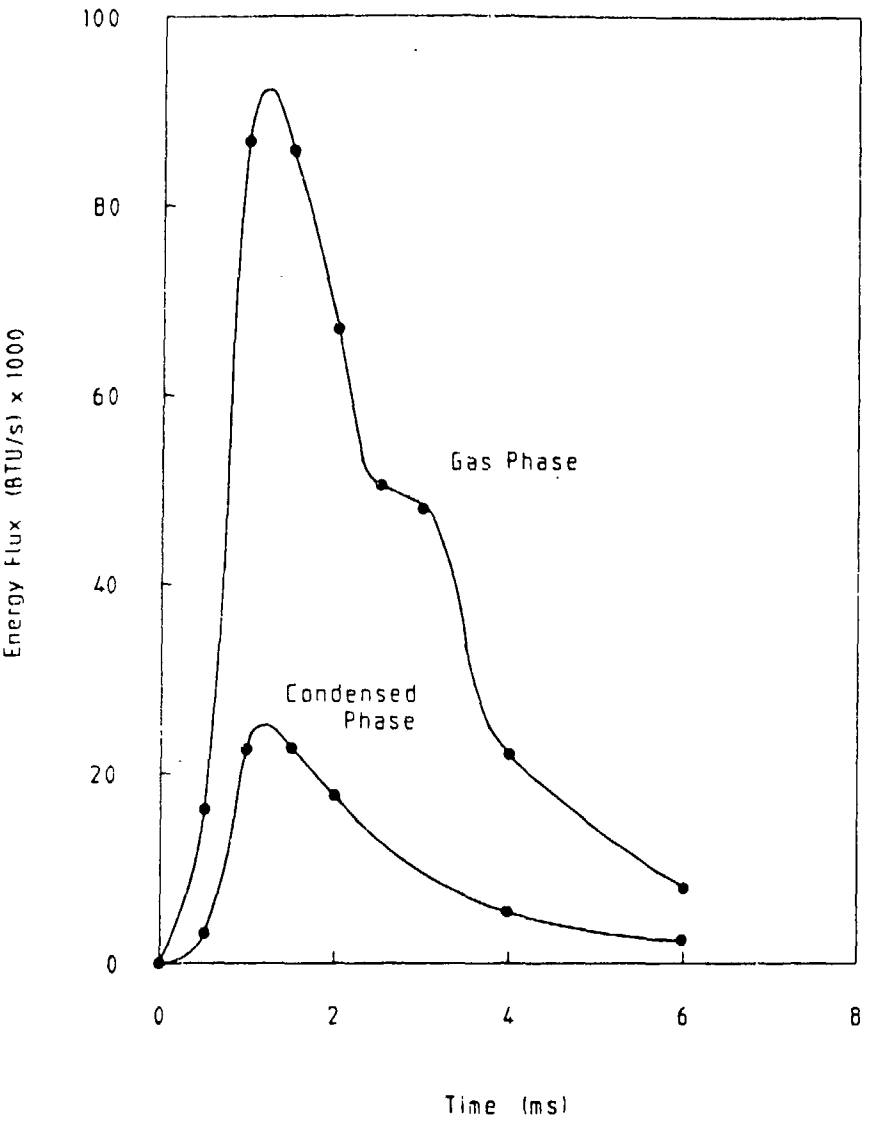

FIGURE 7. PREDICTED (ROCIGN) ENERGY FLUX TO THE PROPELLANT GRAIN FROM 50 g B/KNO_3/RESIN IGNITER

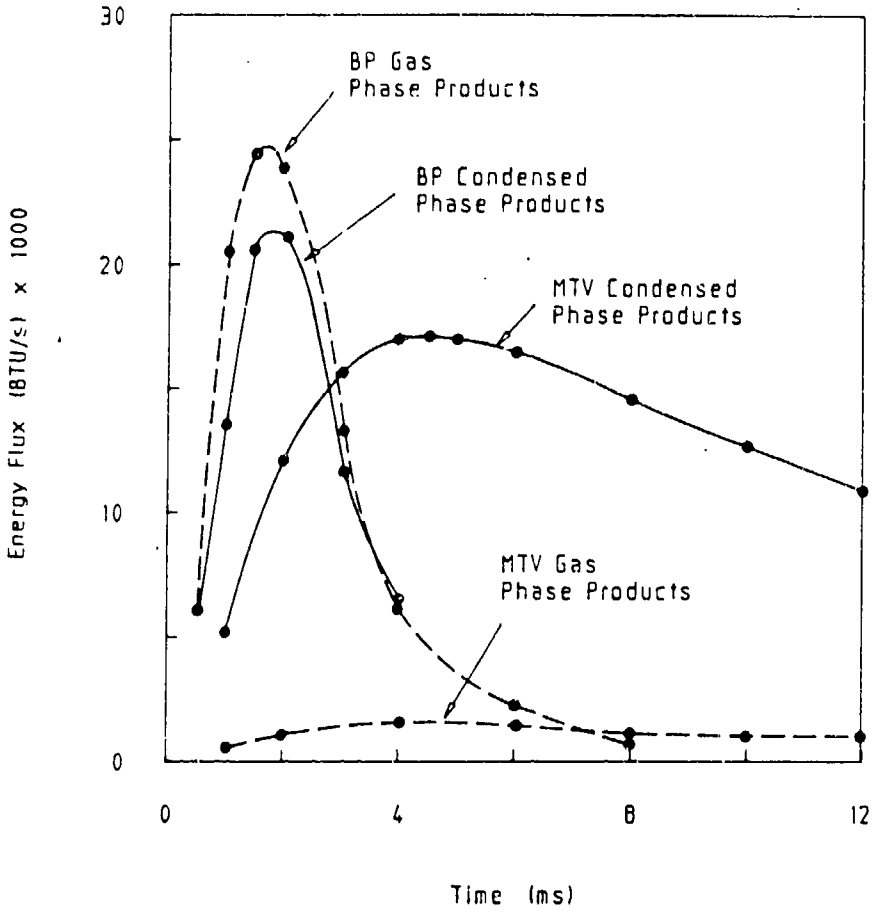

FIGURE 8. PREDICTED (ROCIGN) ENERGY FLUX TO PROPELLANT GRAIN FROM 48 g MTV AND BLACK POWDER IGNITERS

A slightly more extensive code, EBED (19), is also available. Originally developed for gun systems, EBED is being examined for use in predicting ignition performance in solid propellant rocket motors. EBED considers a more complex flow of reaction products along the motor bore and allows vapor-phase condensation, liquid-phase propellant wetting, and solid-particle trapping. These additional capabilities allow evaluation of the heat transfer mechanism to the propellant.

Figure 9 shows the computed heat flux from black powder ignition material to a propellant grain for several fixed time increments as a function of distance from the igniter vents. After 1 ms, the heat transfer from 0 to 7.6 cm includes all active mechanisms: conduction, convection, particle trapping, particle wetting, and condensation-phase change. However, beyond 7.6 cm, the heat transfer rate drops sharply as the stream becomes depleted of liquid phase material. After 2 ms, the grain temperature has been raised enough so that no condensation occurs and the active mechanisms are only liquid wetting, solid particle trapping, and convection. After 6 cm the stream loses its liquid and solid phase leading to the sharp decrease inheat transfer. However, at 7.6 cm, the vapor phase begins to condense out, causing an increase. This overall pattern is repeated for the rest of the time steps. The

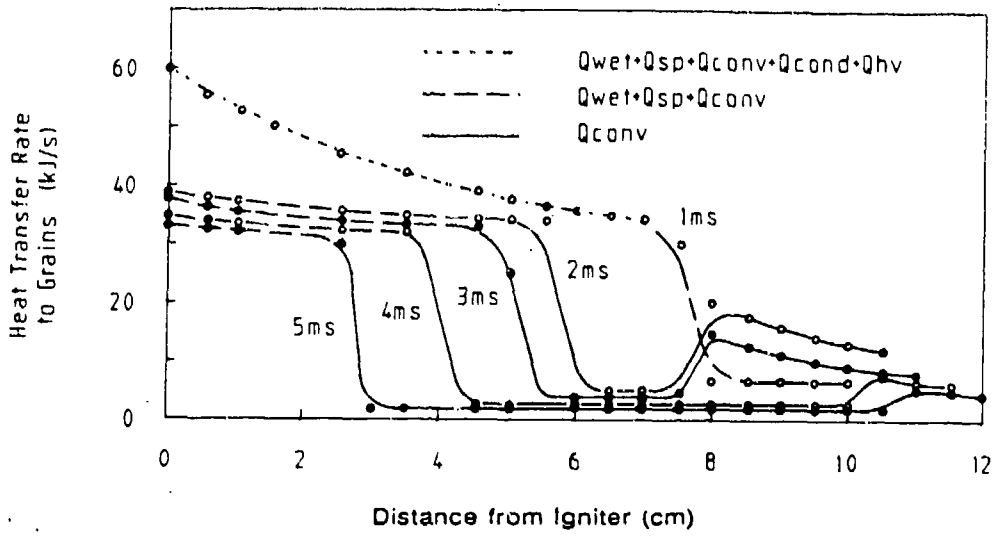

FIGURE 9. HEAT TRANSFER MECHANISMS TO PROPELLANT FROM BLACK POWDER IGNITER STREAM

limitations of the model (apart from those associated with the igniter modeling) are the lack of thermodynamic and transport properties of the reaction products and the weakness of the solid particle trapping and condensation models.

Burn-Rate/Device Modeling

Several other codes are used at NAVORDSTA to fulfill other requirements. The HARDT Code (21) has been implemented for many years and has been used to predict the burn rate of binary delay systems and intermetallics. The code was principally developed for intermetallics but has been used with conventional pyrotechnic delays. Comparison between computed burn rates and experimental values is often poor, but the code does give an order-of-magnitude agreement (10).

The Cartridge Actuated Device Program, CADPROG, is another computer code that enjoys considerable use at NAVORDSTA. This program is, as the name implies, used to simulate the interior ballistics of a cartridge-actuated device (CAD). The code models the combustion of a propellant or pyrotechnic composition (with assistance from the NASA-Lewis code CEC 76) and then translates the pressure developed into mechanical work where a piston moves or causes some other mechanical operation to occur. Although the code has been updated, it follows the basic theory as set down by Holter, et al. (22, 23).

The code handles two general devices — a single-chamber leaking CAD or a dual chamber (or "high-low") leaking CAD. By altering various parameters, the code may be used to model other specific CADs such as closed bombs, and gas generators, or a telescoping piston with a progressively decreasing cross section. The code theory is based on the use of the Abel equation:

$$P_{max} = \frac{F}{1/\rho - \eta}$$

where F is the propellant impetus, ρ the propellant loading density, and η the propellant covolume. The values of F and η are taken from well-known data for the particular propellant of pyrotechnic composition in use.

The single-chamber CAD is shown schematically in Figure 10. Upon ignition of the main charge in the chamber, the resulting gas pressure acts on the base of the piston and imparts an acceleration to it. Since the model involves a leaking CAD, a portion of the gas leaks through the side of the chamber. CADPROG calculates the gas temperature, mass of gas, and gas pressure in the chamber as a function of time. Figure 11 shows the comparison between experimental results and those obtained with the CADPROG code for the acceleration of a 459-lb piston through a distance of 32.25 inches with no chamber leakage.

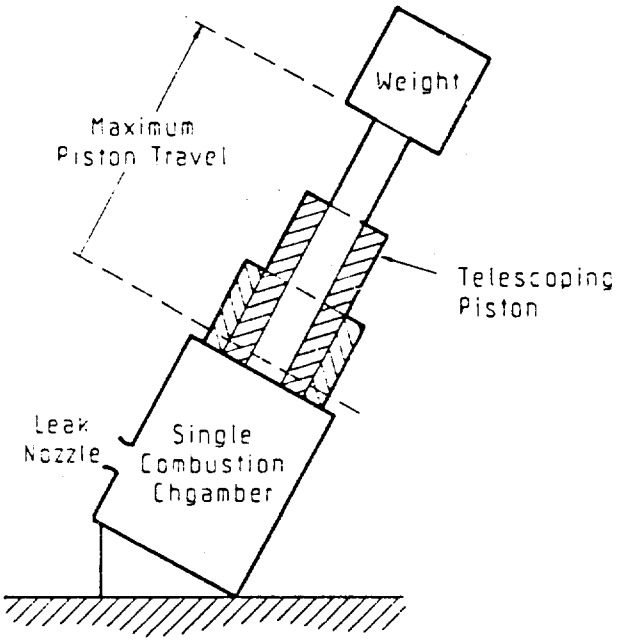

FIGURE 10. SCHEMATIC OF SINGLE CHAMBER TELESCOPING LEAKING CAD

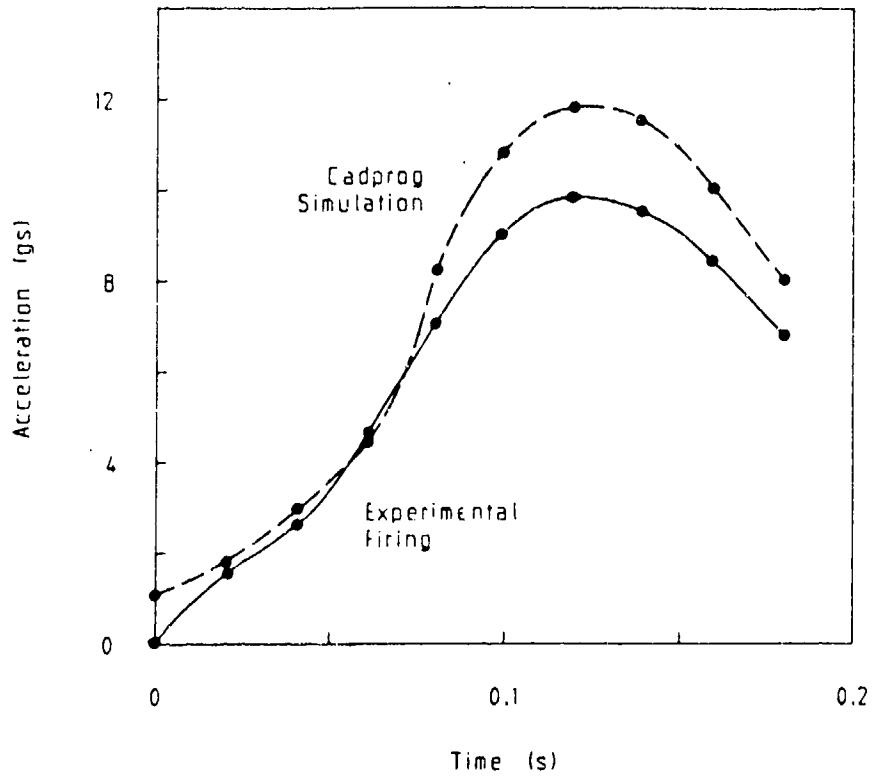

FIGURE 11. RELATIONSHIP BETWEEN ACCELERATION OF THE PISTON WEIGHT AND TIME

A schematic of the dual chamber (or high-low) leaking CAD is shown in Figure 12. This device differs from the single-chamber CAD in that a small diameter orifice connects two chambers. On ignition of the main composition in the high chamber (bottom chamber) the combustive products vent through the orifice into the low chamber. In the low chamber the gases act on the piston and perform mechanical work to move it. Note that in both chambers gases are allowed to leak through side vents. Figure 13 shows the pressure/time behavior in both chambers for a CAD using 9.5 lb of propellant to accelerate a 10,000-lb piston through 0.08 inch.

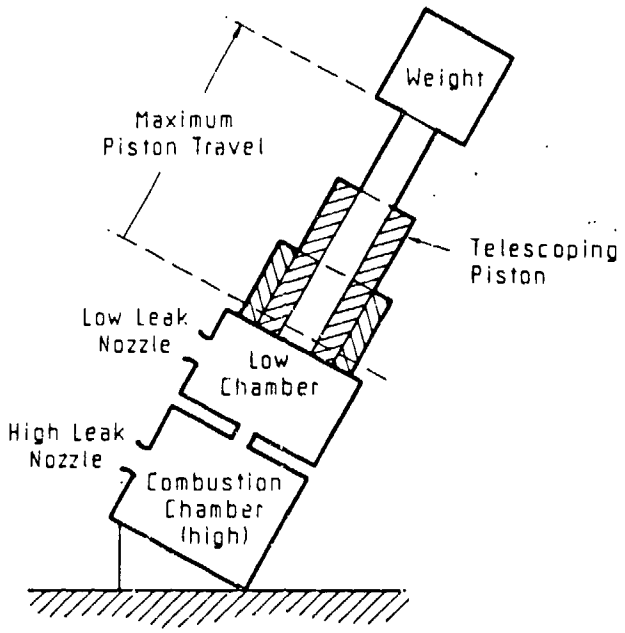

FIGURE 12. SCHEMATIC OF HIGH-LOW TELESCOPING LEAKING CAD

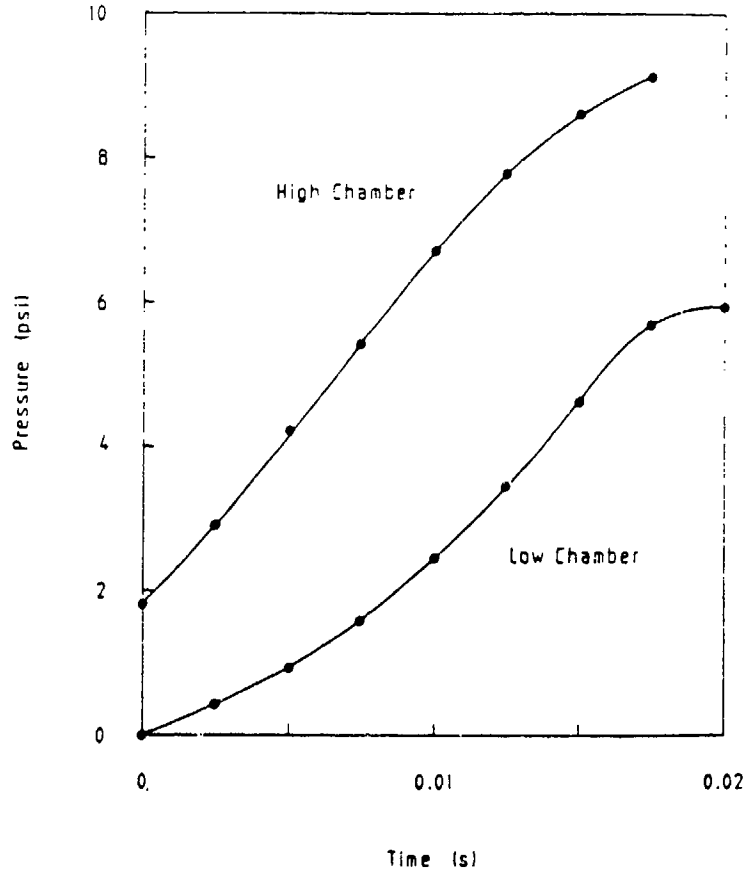

FIGURE 13. HIGH-LOW CHAMBER SIMULATION USING CADPROG FOR A CAD

Apart from data on the ballistics of the CAD, information is also available on the response of various media to such accelerations; e.g., the response and compression of a spinal column which may be used as a measure of injury probability when subjected to the acceleration.

This code is used extensively at NAVORDSTA and draws heavily on calculated or published data for the thermochemical and dynamic behavior of propellants and pyrotechnic compositions. Like the other codes discussed, use of this type of calculated data presents the greatest source of error and results should be viewed with a knowledge of the limitations and range of applicability of the computer code.

CONCLUSIONS

Many models are available from the propellant and explosives communities which can be applied with some success to pyrotechnic systems if used appropriately and their limitations and assumptions are recognized. Often the problems in successfully applying such programs to pyrotechnics result from the high condensed fraction of the output or the lack of basic information on the materials themselves; e.g., chemical impurities and insufficient thermodynamic data.

All the programs presented in this report have been applied to pyrotechnic systems with varying degrees of success. With understanding, minor modifications or additions to the programs or their databases and some perseverence, such programs can save time and money in arriving at solutions to problems in pyrotechnics. Because of the sophistication and cost of developing such programs (well beyond that affordable in the area of pyrotechnics), the pyrotechnist must learn how to use and adapt those programs and models and how best to interpret results. Otherwise, the design of pyrotechnic systems will continue to be viewed and practiced as an art based on "black magic," experience, and intuition instead of the bona fide scientific discipline it is now becoming.

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Appendix

Composition	Ingredients	Proportions (w/w)
MTV	Magnesium	54.0%
	Teflon	30.0%
	Viton A	16.0%
AIA	Zirconium	65.0%
	Iron oxide	25.0%
	Diatomaceous earth	10.0%
B/KNO_3	Boron	23.7%
	Potassium nitrate	70.7%
	Laminac resin	5.6%
$Zr/KClO_4$	Zirconium	46.5%
	Potassium perchlorate	52.5%
	Graphite	1.0%
Black powder	Sulphur	10.4%
	Potassium nitrate	74.0%
	Charcoal	15.6%
PA 101	Basic lead styphnate	53.0%
	Barium nitrate	22.0%
	Tetracene	5.0%
	Aluminum powder	10.0%
	Antimony sulphide	10.0%
M42F1	Boron	9.5%
	Lead oxide	85.5%
	Tetracene	5.0%

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